Chapter 3

RADCOOL - A TOOL FOR MODELING BUILDINGS EQUIPPED WITH RADIANT COOLING SYSTEMS

3.1 Modeling Approach

The review presented in Chapter 2 indicates that commercial buildings equipped with radiant cooling (RC) systems may require less energy and peak power for thermal conditioning than buildings equipped with traditional all-air systems. Unfortunately, because the information currently available is applicable only to a small number of buildings, it is inadequate in assisting the general design and operation of buildings equipped with radiant cooling systems. Moreover, the transient behavior of radiant cooling systems exposed to variable loads defies evaluation by simple calculation. Under these circumstances, a computer program capable of simulating the dynamic effects associated with the functioning of RC systems constitutes a necessary tool for the study of the thermal performance of buildings equipped with radiant cooling systems.

It is often difficult to simulate new technologies with existing building simulation programs (such as DOE-2, BLAST, TRNSYS). This feature can be generally traced back to the initial stages in the development of these programs. In the case of DOE-2, the choice of algorithms was mainly dictated by the limited capabilities of computers in the early 1980s. Specifically, to simplify calculations and reduce simulation time, DOE-2 calculates the heat transfer through building components (walls, windows) with the response factor method.[1] DOE-2 then estimates the cooling and heating loads for each space by using the weighting factor method.[2] Since these modeling methods bypass the calculation of the surface temperature distributions of building components at least in its present stage of development, DOE-2 cannot model buildings equipped with radiant cooling systems. After employing extensive modeling artifices, the few DOE-2 users who have attempted to model existing buildings equipped with radiant cooling systems have failed to produce results that agreed with measurements from these buildings (see for example [2]).

1. The response factor method calculates the heat gain or loss through a building component by reducing the "heat excitation" due to weather conditions, interior loads, etc. to a collection of triangular pulses. The solution of the one-dimensional heat diffusion equation with the triangular pulses as boundary conditions consists of a set of response factors. The response factors provide a quantitative description of the heat transfer through the building component due to the given "heat excitation" [1].

2. The weighting factor method uses z-transfer functions to calculate the cooling and heating loads of a space from instantaneous heat gains or losses (due to heat transfer through building components, interior loads, etc.). The calculation produces a set of parameters that provide a quantitative description of how much of the heat entering the space is stored, where it is stored, and how fast the heat stored is released during later hours [1].

The author designed the program RADCOOL specifically to simulate the dynamic performance of buildings equipped with radiant cooling systems. RADCOOL (described in detail in Appendix A) is a highly modular building simulation tool based on a complete energy-balance calculation.[1] The ultimate goal for RADCOOL is to operate as a DOE-2 module as soon as DOE-2 development will allow the calculation of surface temperature distributions in buildings. Functioning as a DOE-2 module would allow RADCOOL access to the results obtained by other DOE-2 modules such as the module that calculates the direct and diffuse solar radiation incident on a building surface of any orientation, the subroutine that allows access to weather data, etc. This in turn would reduce the preliminary work presently necessary in the RADCOOL simulation process. Incorporating RADCOOL into DOE-2 would also eliminate several limitations currently imposed on RADCOOL simulations (see Section 3.1.2).

3.1.1 Model capabilities

RADCOOL consists of a library of building components, plus a method to assemble these components into numerical building models. Consequently, each building modeled in RADCOOL corresponds to a specific group of assembled components. This allows RADCOOL to simulate buildings with virtually any construction and layout, whether equipped with radiant cooling systems, or with traditional all-air systems. The current capabilities of RADCOOL depend on the components already present in the building component library (see Appendix A). These capabilities can be extended relatively easily by adding new building components to the library.

The results of a RADCOOL calculation provide information about loads, heat extraction rates, air temperature, and surface temperature distributions in a building. RADCOOL can evaluate system sizing and system configuration, and therefore can assist in HVAC system design. RADCOOL can also be used in the evaluation of issues such as controls, and the dynamic response of the building to load changes, and it can be extended to study indoor thermal comfort and building energy use.

3.1.2 Model limitations

Some of the limitations of RADCOOL are associated with current calculation capabilities of computers, while other limitations are associated with the input data required to

1. A complete energy-balance calculation involves (1) setting up the system of equations that describes the thermal behavior of a building structure as a whole, and (2) solving the system with the boundary conditions imposed by the weather, internal loads, and HVAC system operation. A complete-energy balance calculation is more complex and time-consuming than the approach adopted in DOE-2. However, it allows the evaluation of temperature distributions, a feature necessary for modeling buildings equipped with radiant cooling systems.

perform a given simulation.

At the present development stage of computers, the limiting factor for a RADCOOL calculation is the simulation time. The simulation of a structure containing more than one zone, or the simulation of a single-zone space during time periods longer than 10 days, require a few days of elapsed time to complete execution on a SUN workstation using a *SPARC-5* processor. As the use of RADCOOL is presently limited to workstations, the modeling capabilities of RADCOOL are restricted to single-zone structures, and to simulation periods of less than 10 days. Incorporating RADCOOL into DOE-2 as a module should eliminate these limitations.

In principle, RADCOOL can model any type of building structure, assuming that the user provides the thermal properties of the construction materials. RADCOOL can also model the thermal loads associated with any type of building occupancy, lighting, plug loads, and any type of weather-induced boundary conditions for a building, assuming that the user is able to provide all information necessary for the modeling process. In other words, the level of sophistication of the RADCOOL calculations, as well as the degree in which the RADCOOL results approach reality, depend strongly on the inputs supplied by the user.

3.2 Model Evaluation

To evaluate the results obtained from RADCOOL simulations, the ideal test would consist of (1) monitoring a large number of buildings equipped with radiant cooling systems, (2) using RADCOOL to simulate these buildings, and (3) comparing the simulation results with the measurements. Unfortunately, data measured in buildings equipped with radiant cooling systems are not available. Consequently, the evaluation of RADCOOL [3] was limited to: (1) performing an intermodel comparison with DOE-2, and (2) performing a comparison with data measured inside *one* building equipped with a radiant cooling system.

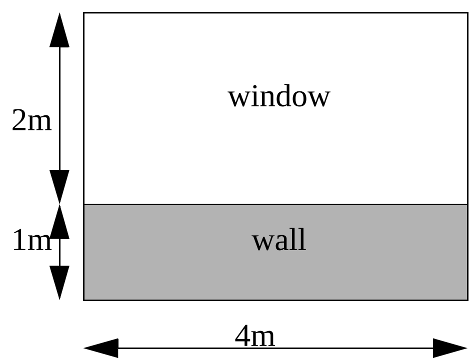
3.2.1 Intermodel comparison with DOE-2

To evaluate the modeling capabilities of RADCOOL, the results obtained by RADCOOL and DOE-2 were compared in a domain where both programs were applicable. Specifically, the intermodel comparison was based on the results obtained from parallel simulations of a single-zone structure that does not incorporate radiant cooling surfaces.

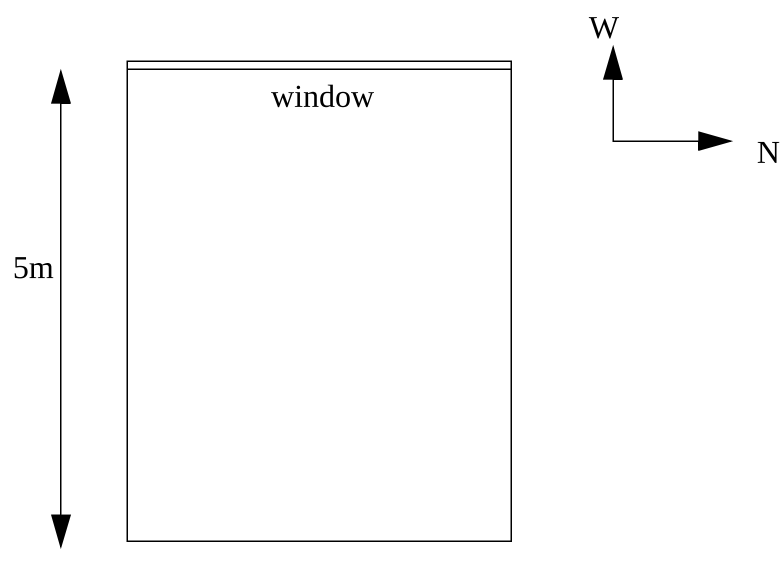
A number of studies have evaluated the modeling capabilities of the DOE-2 building simulation program (see for example [4] and [5]). These studies have found that the results obtained by simulating an existing building in DOE-2 can agree very well with data measured inside the same building.

Description of the inputs to the simulation

The single-zone structure simulated by RADCOOL and DOE-2 is a shed with the dimensions of 4 m x 5 m x 3 m. All vertical walls, and the roof of the structure are exposed to weather conditions. Its floor is in direct contact with the ground. The structure has one window with western exposure. Figure 3.1 shows the spatial geometry and the window location of the single-zone structure.



Elevation - the West-facing wall



The single-zone structure- plan

Figure 3.1. Single-zone structure simulated for the intermodel comparison.

The Red Bluff Typical Meteorological Year (TMY) weather file was used to obtain the weather-induced boundary conditions for the single-zone structure.[1] Thus, the outside air temperature, outside air humidity ratio, direct and diffuse solar radiation, cloud cover, ground temperature, etc. that constitute input for the simulation correspond to the weather conditions typical for Red Bluff, California.

To provide a realistic basis for intermodel comparison, the "pre-heating" procedure typical for DOE-2 was simulated in both programs. The "pre-heating" procedure ensures consistent and well-defined initial conditions, adjusted to the climate in which the structure is modeled. In DOE-2 the "pre-heating" procedure consists of modeling the structure with weather-induced boundary conditions obtained by repeating several times the weather for the first day to be modeled. As the intermodel comparison is based on the indoor results obtained by simulating the structure with the weather-induced boundary conditions corresponding to June 1 in Red Bluff, the "pre-heating" procedure consists of simulating the single-zone structure with boundary conditions obtained by repeating seven times the weather conditions for June 1, and using the results as initial conditions.

The intermodel comparison aimed to show the similarities, or discrepancies, in the heat transfer calculations performed by RADCOOL and DOE-2. Consequently, no internal loads, mechanical cooling or ventilation, or infiltration were modeled for the test room.

To compare the results of the two programs for different types of building construction, three wall assemblies were modeled (Figure 3.2).

For simplicity, the four vertical walls, roof and floor of the single-zone structure were simulated as having the same material composition. The material properties simulated in the intermodel comparison are listed in Table 3.1. The simulation assumptions are summarized in Table 3.2.

Table 3.1. Material properties used in the intermodel comparison.

	Density [kg/m^3]	**Specific heat [kJ/kg-K]**	**Conductivity [W/m-K]**
Concrete	2400	1.04	1.80
Wood	800	2.20	0.20
Gypsum board	1000	0.80	0.40
Fiberglass	90	0.60	0.036
Glass	2700	0.84	0.78

1. A TMY file is created by selecting the most representative calendar months from surface meteorological data and solar radiation data recorded on an hourly basis over a 20- or 30-year period at a given location. A TMY weather file is therefore a weather file representative for the weather at that location.

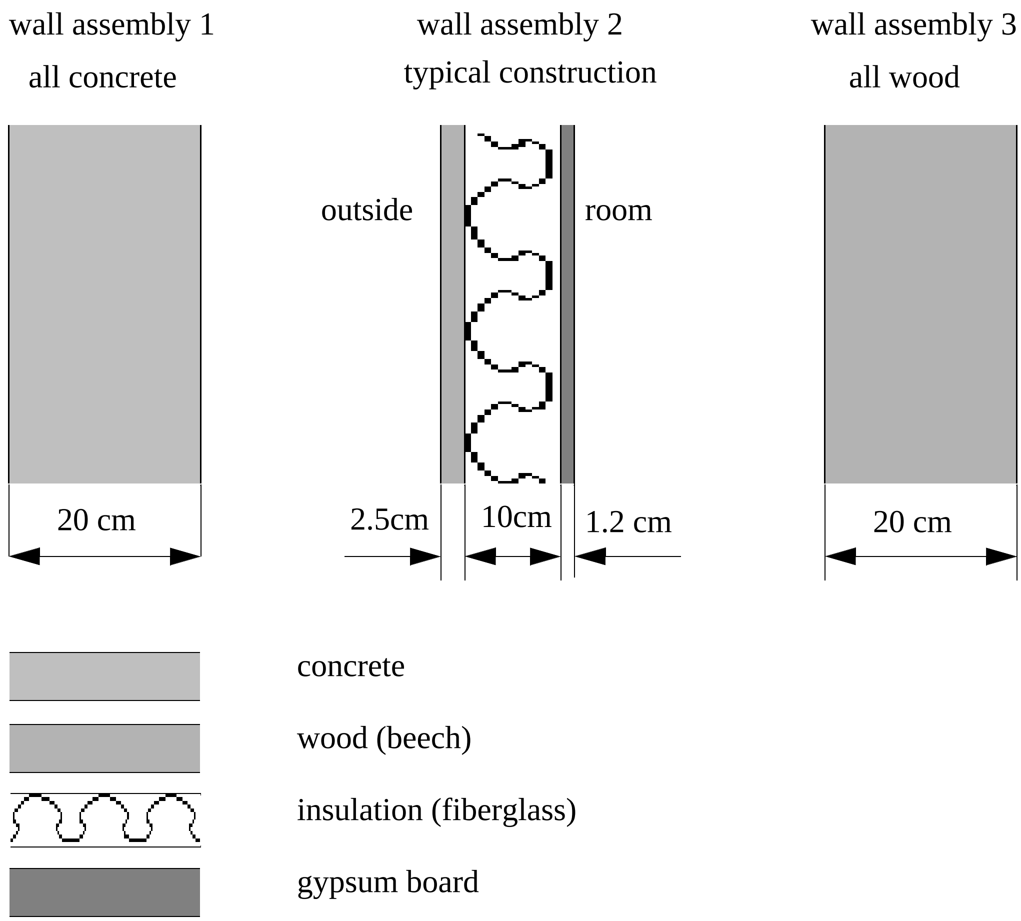


Figure 3.2. The three wall assemblies simulated for the intermodel comparison.

Results

Figures 3.3 - 3.5 show the indoor air temperature of the single-zone structure as simulated by RADCOOL and DOE-2 for the three types of wall assemblies described in Figure 3.2. The RADCOOL indoor air temperatures presented in these figures are the result of several iterations in which certain coefficients were adjusted to match the DOE-2 assumptions as closely as possible. Once adjusted, the same coefficients were used for all three structures.[1] For the purpose of comparison, the Figures 3.3 - 3.5 also contain

1. The RADCOOL input for the three structures contains the same parameters except for the material properties of the wall assemblies.

TABLE 3.2. Summary of assumptions for the intermodel comparison.

Assumptions	RADCOOL and DOE-2
Geographical location	Red Bluff, CA
Structure geometry, dimensions and orientation	Figure 3.1
Window exposure	western
Construction of vertical walls, roof and floor	Figure 3.2 and Table 3.2
Window type	single-pane, clear glass
Internal loads	none
Mechanical cooling	no
Mechanical ventilation	no
Infiltration	no

the outside air temperature.

The concrete walls of the first structure have high conductivity (1.8 W/m-K), and high thermal mass. During daytime, the walls and roof are exposed to direct solar radiation on the exterior side, and to the solar radiation entering through the window on the interior side. This incident heat is conducted into the walls and stored, warming them up. At the same time, solar radiation entering through the window, and convective heat transfer with the warm walls warm up the indoor air (Figure 3.3). Because a large fraction of the solar radiation incident on the structure is stored in the walls, the indoor air reaches its maximum temperature a few hours after the outside air. Heat storage in the walls also reduces the diurnal amplitude of the indoor air temperature as compared to the outside air.

The second wall assembly represents a typical exterior wall. An insulation layer is "sandwiched" between an exterior wood board and an interior gypsumboard layers. The whole structure is designed to minimize the heat conducted through the building envelope. Because the walls are highly insulated, solar radiation entering through the window during the day warms up mainly the gypsumboard layer and the indoor air (Figure 3.4). Then the indoor air (along with the structure) cools down at night mainly due to heat loss through the window. Overall, the diurnal variation of the indoor air temperature the second structure is much higher compared to that of the outside air. The time of maximum of the indoor air temperature is much delayed as a result of storage effects into thegypsumboard layer, and of the insulated character of the structure.

The wood walls of the third structure have lower conductivity (0.2 W/m-K) than the

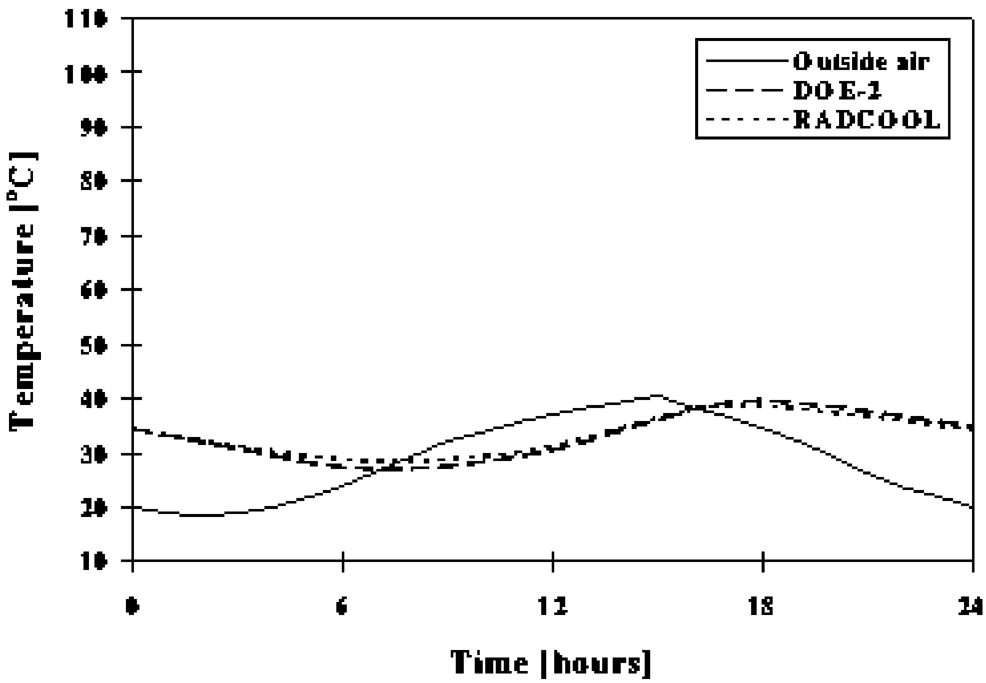


Figure 3.3. Outside and indoor air temperature: wall assembly 1 (concrete).

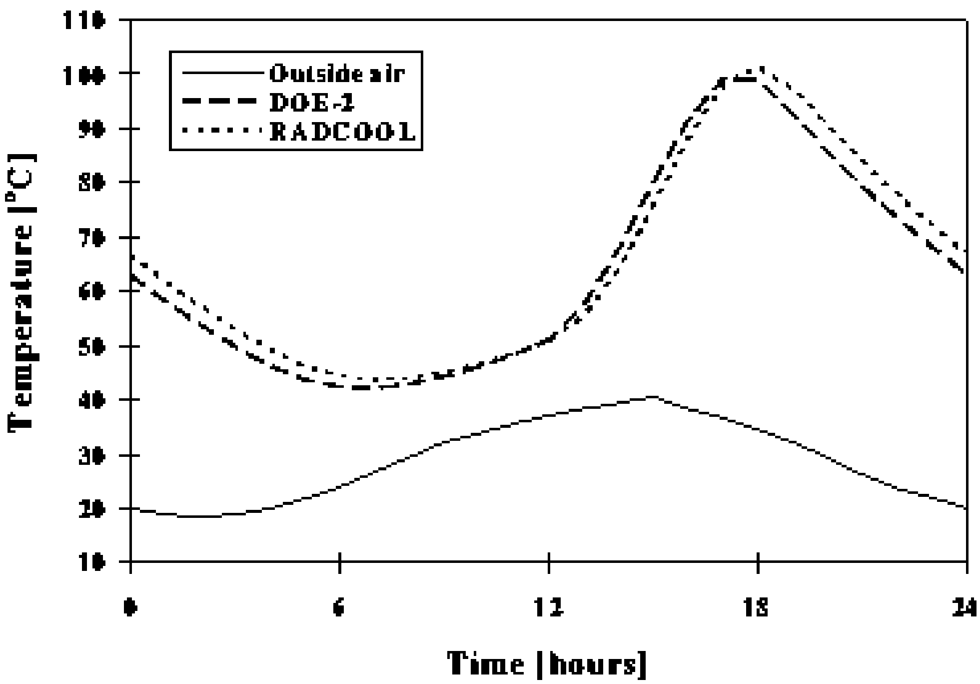


Figure 3.4. Outside and indoor air temperature: wall assembly 2 (typical construction).

concrete walls of the first structure. As a result, less heat is stored in the wall itself, because less heat is conducted from the surfaces of the wall towards the inside of the wall. The indoor air of the structure heats mainly due to the solar radiation entering the window (Figure 3.5). The indoor air temperature of the wood structure is higher, but it has a lower diurnal variation when compared to the indoor air temperature of the concrete structure.

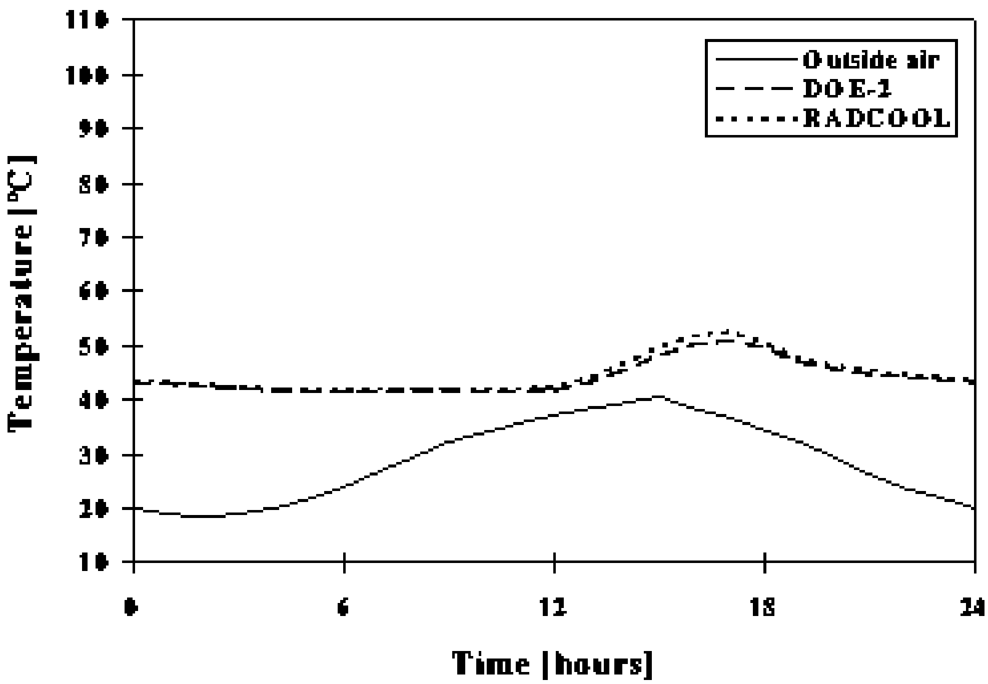


Figure 3.5. Outside and indoor air temperature: wall assembly 3 (wood).

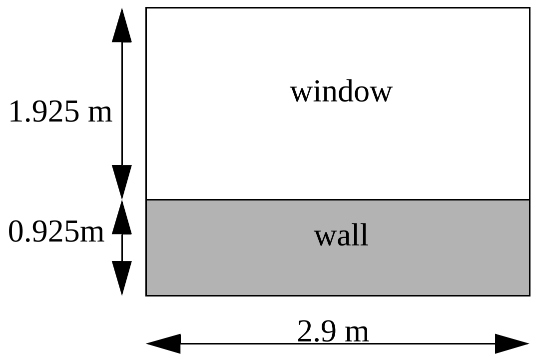
The intermodel comparison shows that the predictions for the indoor air temperature made by RADCOOL and DOE-2 are very similar. The predicted temperatures agree within 2° C.

3.2.2 Comparison with measured data

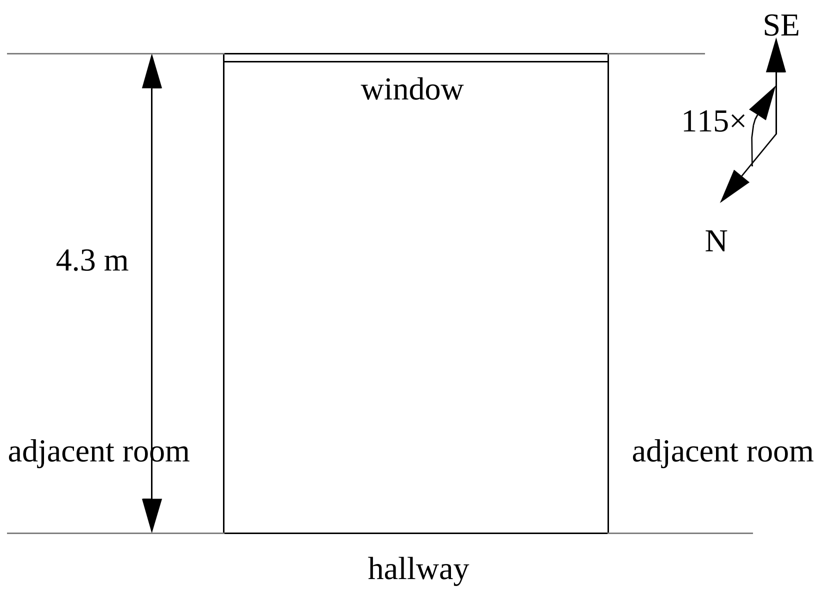
The performance of RADCOOL was also tested by comparing its results with measurements from a building equipped with a radiant core cooling system.

The DOW-Europe test room

Measurements were performed in the Swiss building housing the European headquarters of DOW Chemicals (geographical location 47 °N and 9 °E). The test room monitored to determine the performance of the core-cooling radiant system is located on the top floor of the building (height = 12.8 m above the ground). The room has the dimensions of 2.9 m x 4.3 m x 2.85 m, and its facade is oriented 65° East of South (see Figure 3.6).



Elevation - the SE-facing wall



The test room - plan

Figure 3.6. The DOW Chemicals test room orientation and layout.

Wall composition

Figures 3.7 and 3.8 show the composition of the test room walls. The room's exterior

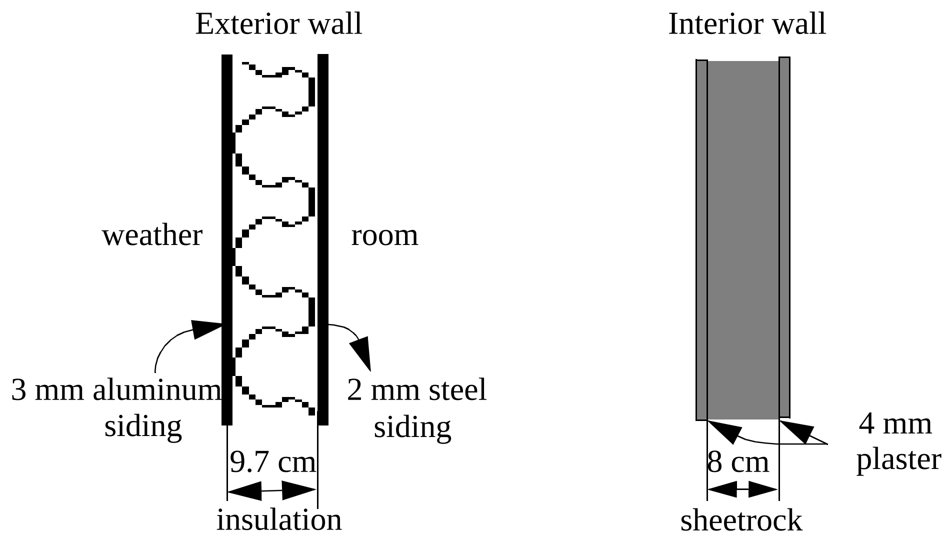


Figure 3.7. Composition of the vertical walls in the DOW Chemicals test room.

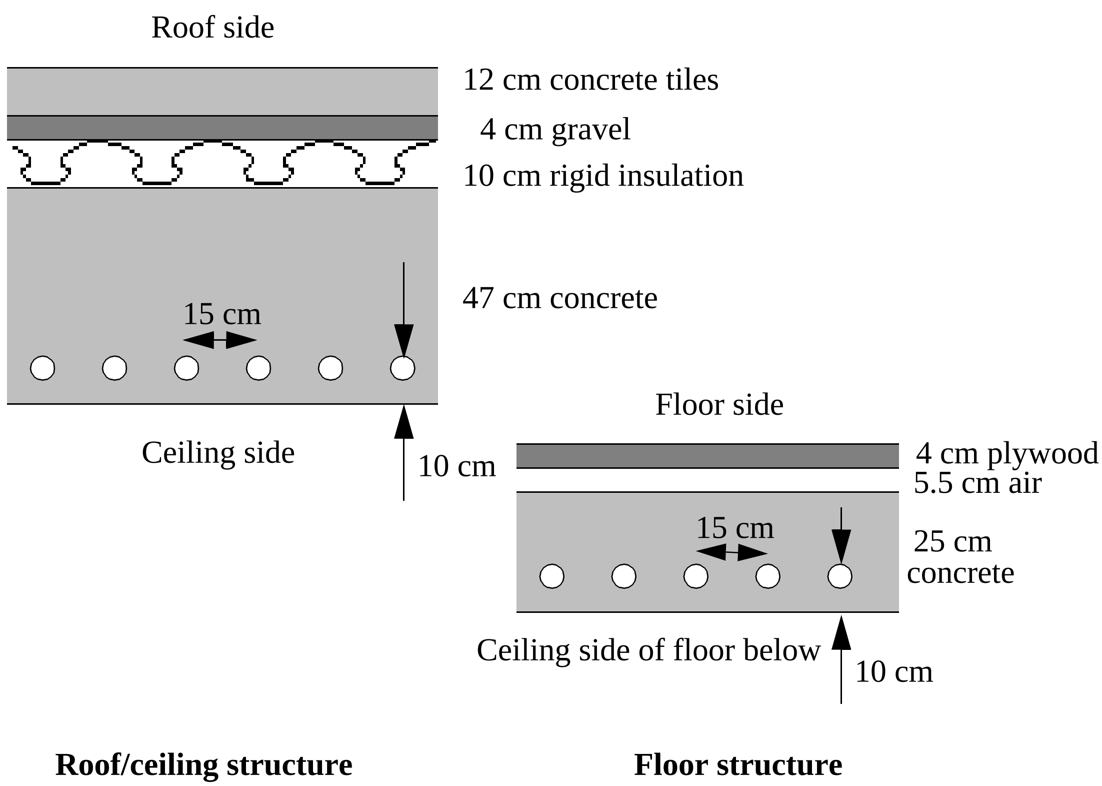


Figure 3.8. Composition of the roof and floor in the DOW Chemicals test room.

facade has the overall dimensions of 2.9 m x 2.85 m. The facade incorporates a double-pane window of 2.9 m x 1.925 m and an overall U-value of 1.75 W/m^2-K [6]. The wall below the window has the dimensions of 2.9 m x 0.925 m and an overall U-value of 0.34 W/m^2-K. Automatic shades are installed over the windows, on the exterior of the facade. The shades are operated by a sensor parallel to the window surface. A control mechanism closes the shades when the total (direct plus diffuse) solar radiation incident on the window becomes higher than the threshold of 120 W/m^2, and opens them when the total solar radiation incident on the window drops below 120 W/m^2.

The interior walls consist of sheetrock and plaster.

The ceiling of the test room (which is also the roof of the building) has the dimensions of 2.9 m x 4.3 m. Its overall U-value is 0.32 W/m^2-K.

The test room has a raised floor over the cooled concrete slab of the room below. The dimensions of the floor are also 2.9 m x 4.3 m, and its overall U-value is 2.5 W/m^2-K.

The material properties used in the comparison between RADCOOL results and measured data are presented in Table 3.3.

TABLE 3.3. Material properties used in the comparison with measured data.

	Density [kg/m^3]	**Specific heat [kJ/kg-K]**	**Conductivity [W/m-K]**
Insulation batt	85	830	0.034
Plaster board	1400	900	0.70
Sheetrock	1000	1100	0.40
Concrete	2400	1040	1.80
Rigid insulation	33	1400	0.032
Gravel	1650	900	0.70
Plywood	800	2500	0.15

Loads

At the time when measurements were performed inside the DOW Chemicals test room, internal loads were modeled by controlling the operation of several light bulbs installed in the room. This measure was considered necessary in order to eliminate any unexpected results that might occur due to random occupant behavior. Occupancy was physically simulated as: 436 W (35 W/m^2), from 8 a.m. to 12 p.m. and from 1 p.m. to 5 p.m., Monday through Friday. No occupancy was simulated during the weekend.

The solar radiation intensities necessary for simulation of the test room were obtained from weather tapes recorded at a weather station located at 20 km distance from the building. There are no tall buildings on the site, and the DOW Chemicals building is not shaded by any horizon obstacles.

Blower-door tests performed in the test room showed that the infiltration rate was 0.2 ACH. A constant infiltration rate of 0.2 ACH was assumed in RADCOOL, even during the periods when the ventilation system supplies air to the building.

System

The cooled ceiling. The radiant system inside the core cooling ceiling is composed of water pipe registers that cover an area of 8.3 m^2 each.[1] The pipes are made of polyethylene, have 16 mm exterior and 12 mm interior diameters, and are placed 15 cm on centers, 10 cm deep inside the concrete. The water flow in each register is constant throughout the day at 100 l/h. Given the size of the test room, 1.5 registers cover the cooled ceiling, so a total of 150 l/h (0.042 kg/s) of water flows through the core cooling ceiling. The temperature of the supply water was recorded and is thus available for the simulation.

Ventilation. Air is supplied to the room at a rate of 1.1 ACH (36 m^3/h) during "occupancy hours" and at the rate of 0.55 ACH during "off-occupancy" hours. The temperature of the supply air was measured and is available for the simulation.

Boundary conditions

The modeling of the test room in RADCOOL requires information regarding the thermal behavior of the room boundaries. Boundary conditions that can be used in the modeling process are: the temperatures of the wall surfaces inside the room, the temperatures of the wall surfaces in the adjacent rooms, or the air temperatures in the adjacent rooms.

No measurements of surface temperatures were made while the test room was monitored. The only air temperature measurements were made in (1) the test room, (2) one adjacent room, and (3) the hallway (see Figure 3.6). Under these circumstances, several assumptions were necessary in the modeling of the test room.

The two rooms adjacent to the test room were modeled as having equal air temperatures. The air temperature available from one adjacent room was thus used as a boundary condition on both "lateral walls" of the test room.

The air temperature in the room located below the test room was assumed to be equal to the air temperature in the test room. Since one of the goals of the RADCOOL simulation

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1. Figure 2.4 in Chapter 2 is an example of a cooling grid register. The registers used in core cooling ceilings are similar, but composed of thicker pipes that are spaced at 10-20 cm on centers. When assembling a core cooling ceiling, registers are imbedded in concrete side by side and connected. From the point of view of the water flow, there is "parallel" connection among registers.

was to calculate the indoor air temperature in the test room, the measured air temperature could not be used as input to the simulation. Consequently, RADCOOL assumed that the air temperature in the room below (boundary condition) was equal to the calculated test room temperature.

The test room air temperature was measured by two sensors, one located 10 cm above the floor (ankle level) and the other located at 1.1 m above the floor (head level of a seated person). The sensor located at ankle level reports a lower temperature than the sensor located at head level. The report accompanying the data [6] states that the floor surface temperature was approximately equal to the air temperature measured at ankle level. The RADCOOL simulation assumed that the indoor air of the test room was well mixed. The temperature of the air near the floor was therefore considered to be equal to the average room air temperature.

Measurements of the inlet water temperature in the ceiling registers of the test room were available, but measurements of the inlet water temperature in the ceiling registers of the room below (lower side of the floor) were not available. Since all the ceiling registers of the DOW Chemical building receive the cool supply water from the same chiller, the RADCOOL simulation assumed that the two inlet water temperatures were equal.

Measurements of the outside air temperature were made in the vicinity of the building. The outside air temperature was also available from weather tapes recorded at a weather station located at 20 km distance from the building. To capture microclimate characteristics, the RADCOOL simulation used the air temperature measured near the building as input. Solar measurements from the weather station were used as input for the direct and diffuse solar radiation incident on the exterior wall of the test room.

The operation of the window shades was “measured,” but the variation of the air temperature of the test room does not agree with the window shade operation reported. Specifically, the window shades are reported to have been open during the last two days of the simulated period (weekend days), but the air temperature in the test room is not high enough to support this information. Consequently, the RADCOOL simulation used a window shade schedule calculated on the basis of the 120 W/m^2 threshold during working days, and modeled the window shades as being shut during the weekend.

The RADCOOL simulation assumed that the absorption and transmission coefficients of the window panes were constant over time. Absorption coefficients of 0.05 and transmission coefficients of 0.6 were used for both direct and diffuse radiation. In reality these coefficients are not equal for direct and diffuse radiation; in addition, they vary over time and are functions of the position of the sun relative to the window surface.

Other modeling assumptions

As stated in Appendix A, to avoid lengthy calculations regarding the distribution of the solar load inside the space, RADCOOL adopted the DOE-2 procedure in which each wall receives a certain percentage of the solar radiation entering the space. In the case of the DOW-Europe test room, the following percentages were modeled: the floor received 57% of the solar radiation entering the space, the vertical walls and the ceiling received area-weighed shares of 38% of the solar radiation entering the space, and the remaining 5% of the solar radiation entering the space was reflected back out through the window.

To simulate the loads generated inside the space in RADCOOL, some assumptions related to the character of these loads were necessary. As stated above, a total load of 456 W was physically modeled by operating electrical lamps inside the space. The RADCOOL simulation assumed that 35% of the total load (150 W) represented convective loads and 65% (286 W) represented radiant loads. The simulation assumptions are summarized in Table 3.4.

TABLE 3.4. Summary of assumptions for the comparison with measured data.

Assumptions	RADCOOL
Geographical location	47 °N, 9 °E
Structure geometry, dimensions and orientation	Figure 3.6
Window exposure	65 ° east of south
Construction of vertical walls, roof and floor	Figures 3.7 and 3.8, and Table 3.2
Window type	double-pane, tinted glass U-value = 1.75 W/m^2-K
Window shading	external shades controlled by radiation sensor parallel to window surface
Internal loads	35 W/m^2, 35% convective and 65% radiative
Internal load schedule	8 a.m. to 12 p.m. and 1 p.m. to 5 p.m., Monday through Friday; no internal load on weekends
Mechanical cooling	core-cooling ceiling
Water volume flow and inlet temperature	180 l/h, 24 h/day measured, variable temperature
Ventilation air volume flow and inlet temperature	36 m^3/h from 8 a.m. to 5 p.m., and 18 m^3/h from 5 p.m. to 8 a.m. Monday through Friday, and 18 m^3/h on weekends; measured, variable temperature
Infiltration	0.2 ACH, constant rate

Results

To evaluate RADCOOL's performance, simulated indoor air temperatures were compared with the measurements of the air temperature at 1.1 m above the floor. Figure 3.9 shows this comparison. The RADCOOL air temperature represents the result of the first attempt to model the test room. Fine-tuning of the RADCOOL input is possible, but requires access to detailed building information.

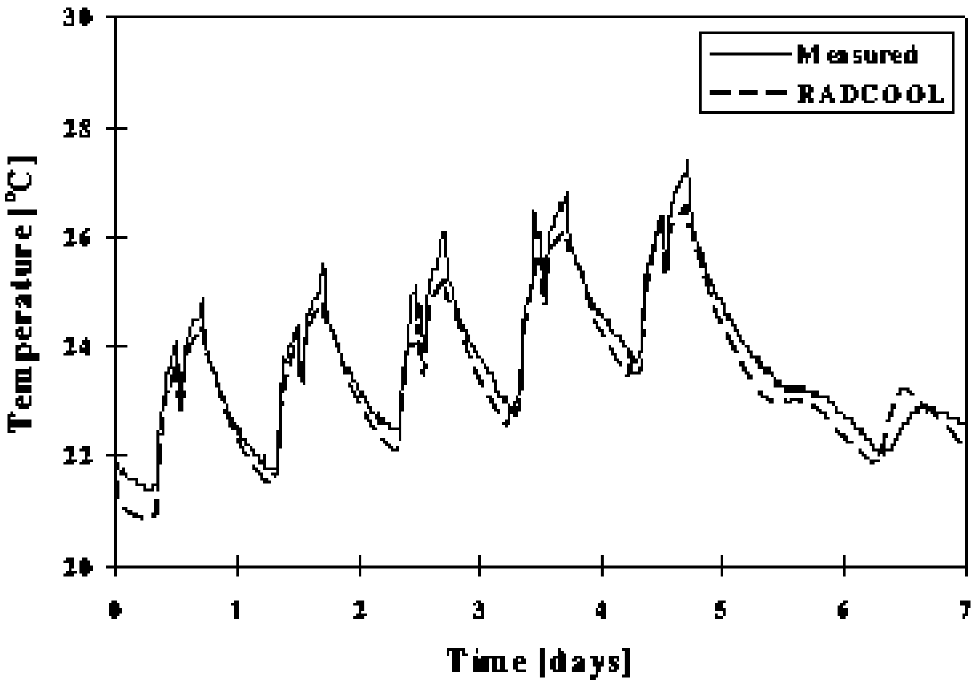

Figure 3.9. Air temperature inside the DOW Chemicals test room.

The RADCOOL simulation results for the room air temperature show good agreement with the air temperature measured at 1.1 m above the floor. There are two minor differences between the two curves. The first difference is a small discrepancy between the times at which the air temperature curves reach the daily minima. The RADCOOL results predict that the building cools faster than indicated by the measurements. The second difference consists of a discrepancy between the predicted and the measured maximum air temperature. On the first 6 days the RADCOOL simulation prediction for the daily maximum is lower than the value measured, while on day 7 the RADCOOL prediction is higher. For the last day of the simulation, RADCOOL also predicts that the peak temperature would occur about four hours earlier than the time of the measured peak. Both differences might be due to a discrepancy between the simulated operation and the real operation of the window shades. If the building orientation used to calculate the schedule of the window shades is off by a few degrees, the real solar heat gain into the test room is different than that simulated, and it elicits a different thermal response from the building envelope. Consequently, the indoor air temperature predicted by RADCOOL is slightly different from the indoor air temperature measured in the test room because the orientation of the building modeled by RADCOOL may be slightly different when compared to the orientation of the real DOW Chemicals building.

3.3 Conclusions

Section 3.2 shows that there is good agreement between the results of the RADCOOL simulations and the results of DOE-2 simulations, and between the results of the RADCOOL simulations and measured data. There is a good chance that, if future RADCOOL modeling is performed similarly, the RADCOOL predictions regarding the operation and functioning of “passive” structures, or of single-zone structures equipped with radiant cooling systems, will be as reliable as those reported in this Chapter.

3.4 Future Work

The present capabilities of RADCOOL (see Section 3.1 and Appendix A) limit the use of the program to a specific class of problems. There are certain modules which, if added to the current library, would allow the RADCOOL user to study a much larger variety of problems. The following paragraphs will describe those modules.

Room air stratification

The air stratification occurring in buildings equipped with radiant cooling systems is significantly different from the air stratification occurring in buildings conditioned by conventional HVAC systems. A radiant cooling ceiling produces a relatively uniform vertical temperature, except in the vicinity of the ceiling.

Because the ceiling of a building equipped with radiant cooling system is cold, the air next to it is cooled by convection. This leads to the appearance of a steep temperature gradient near the ceiling, as the air close to the ceiling becomes colder than the air in the rest of the space. This gradient plays an important role in the functioning of radiant cooling system, because generally the temperature of the contents of the space is close to the air temperature. A high air temperature gradient near the ceiling allows the system to remove large cooling loads. However, if the air in the vicinity of the ceiling becomes too cold (as may happen in the case when the ceiling much colder than necessary for internal load removal), it will move downward and a cold air draft will result [7]. A cold air down-draft has two major consequences. First, depending on the air velocity, a cold air draft might reduce indoor comfort. Second, assuming that the radiant cooling system is combined with a displacement ventilation system, a significant cold air down-draft would interfere with the efficient functioning of the displacement ventilation system: it would cause the contaminated air near the ceiling to mix with the room air, thus reducing air quality inside the space.

While none of the investigations into the performance of radiant cooling systems has reported the existence of cold air down-draft, there is some risk that it may occur in the future. These considerations show the importance of modeling the air movement inside spaces cooled by radiant cooling systems. Computational fluid dynamics (CFD) programs are available that can model air movement inside virtually any space. Given the present computation capabilities of computers (excluding CRAYs), it is still unrealistic to attempt an integration of RADCOOL with a CFD program. However, results from CFD research could be used to derive a “simplified CFD model” describing the air movement inside a space cooled by a radiant cooling system. This simplified model could then be implemented as a separate module in the RADCOOL library. The RADCOOL user would thus be able to make some estimates of (1) the air stratification problem, and (2) the air velocities inside the modeled space, without causing a significant increase of the computation time.

There are several reasons why a “simplified CFD model” has not already been added to the RADCOOL library. First, measurements inside buildings newly-equipped with radiant cooling systems indicate that the indoor conditions are comfortable. Furthermore, there are virtually no documented building occupant complaints regarding the performance of the radiant systems currently available on the market.[1] The development of the “simplified CFD model” was therefore considered secondary to the development of the other components of RADCOOL. Second, deriving the “simplified CFD model” implies access to a CFD program, and expertise to use this program. Neither of these conditions was fulfilled within the time-frame of the present thesis. Third, such a project would need financial support. Assuming that expertise, access, and financial support are available in the future, the addition of a “simplified CFD model” to RADCOOL would provide additional information regarding the performance of buildings equipped with radiant cooling systems.

Thermal comfort and radiant temperature at the occupant location

As stated in Appendix A, RADCOOL calculates only the long-wave radiation exchange between the surfaces (walls, windows, ceiling, floor) of the modeled space. A module

1. The Kaiser Building in Oakland, California, built in the 1950s, was equipped with one of the first radiant systems. A study conducted there in 1994 [8] showed this early system fails to provide acceptable thermal comfort. The study also showed that replacing the old radiant panels with the improved panels available on the market today would simultaneously restore comfort to the building *and* save 50% of the current energy consumption due to air-conditioning. The proposed project was never completed, as the building owner considered that replacing the existing chiller with a more powerful model was preferable.

that calculates the long-wave radiation exchange between the occupants of a space and the envelope of the space would be a useful addition to the RADCOOL library. The addition of this module to the RADCOOL library together with the room air movement module would provide the user with access to a complete set of thermal comfort variables.

Cooling sources

The RADCOOL user is currently limited to modeling a cooled and ventilated single-zone space. RADCOOL does not model the mechanisms by which the cooling agents (water and/or air) are conditioned. Thus, a RADCOOL simulation assumes that water at a given temperature, and air at a given temperature and humidity ratio, are always available as required to meet the cooling loads.

A number of modules that simulate the behavior of cooling sources are already available for implementation in the RADCOOL library. For example, Ranval [9] proposes a module that simulates the behavior of a cooling tower. Testing the performance of a cooling source, however, requires the simultaneous implementation of several cooling modules in the RADCOOL library, and access to benchmark data describing the performance of that cooling source (design specifications, or access to measured data).

3.5 References

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